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4 **A prefiltering version of the Kalman filter with new numerical integration formulas for Riccati equations**
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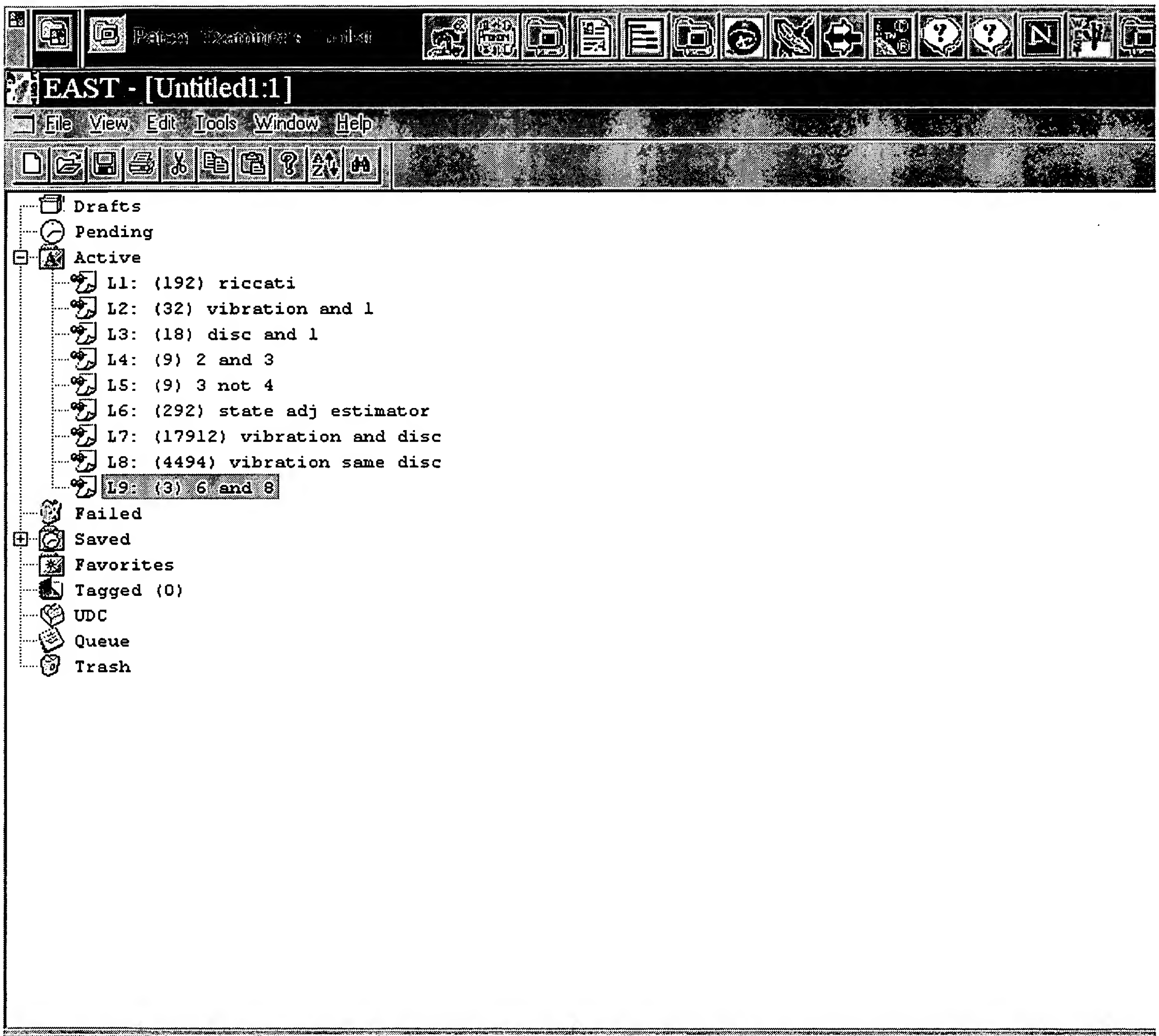

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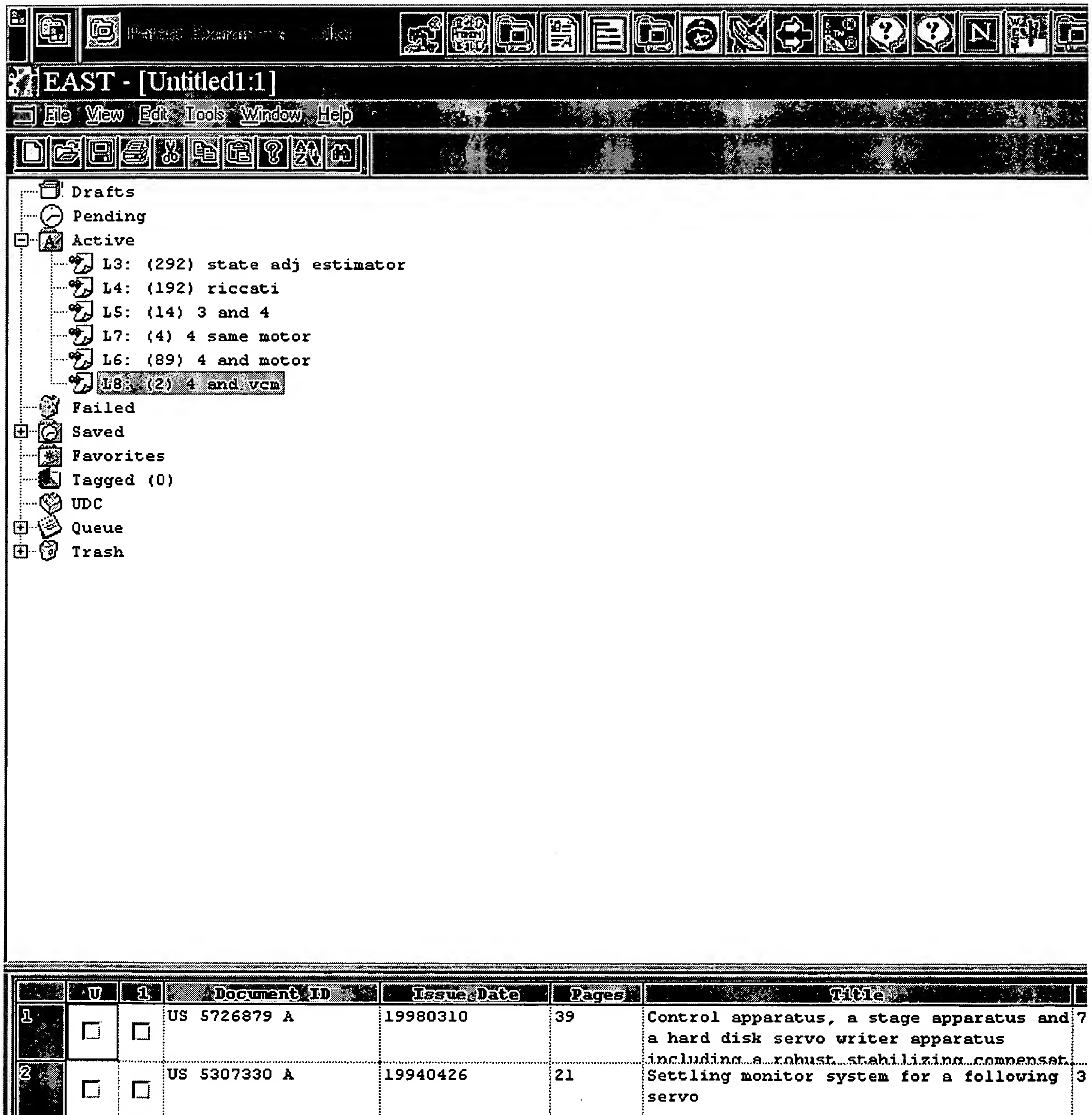

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Peng Shi; Boukas, E.-K.; Agarwal, R.K.;
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The Hinf model matching approach to motor tracking control system

Jee Ming Lee
Dept. of Electr. Eng., Nat. TaipeiInst. of Technol., Taipei, Taiwan;

This paper appears in: **Industrial Automation and Control: Emerging Technologies, 1995., International IEEE/IAS Conference on**

Meeting Date: 05/22/1995 - 05/27/1995
Publication Date: 22-27 May 1995
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On page(s): 624 - 631
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Inspec Accession Number: 5106087

Abstract:
The H^∞ model matching algorithm is proposed for the robust motor tracking control of linear time-varying multi-input, single-output uncertain system. This control method is verified by the system of the permanent magnet DC motor to improve the drive performance and reduce sensitivity of parameter variations, nonlinear effects, and other disturbances such as load changes and backlash. The matching model is used to identify the H^∞ tuning controller with bounded noise energy and minimized tracking error. An algorithm based on discrete Ricatti equation and H^∞ interpolation theory is used to solve the uncertain internal modeling and noise measurement issues in the tracking control system. The adaptive tuning controller effectively controls the presence of external disturbances, and identifies the rapid jumping and slow changing trajectory of the system. The effectiveness of the H^∞ model matching controller for the motor tracking control system is demonstrated by using the developed H^∞ adaptive tuning software controller. The H^∞ model matching control method is examined through computer simulation, and then tested in a real time microprocessor-controlled drive system. Experimental results based on PC based microcomputer implementation are presented to illustrate improved response and robust performance

Index Terms:
DC motor drives H&infin control H&infin interpolation theory H&infin model matching algorithm H&infin tuning controller MISO system PC-based microcomputer implementation **Riccati**

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The Hinf Model Matching Approach to Motor Tracking Control System

JeeMing Lee
Department of Electrical Engineering
National Taipei Institute of Technology

ABSTRACT

The H^∞ model matching algorithm is proposed for the robust motor tracking control of linear time-varying multi-input, single-output uncertain system. This control method is verified by the system of the permanent magnet DC motor to improve the drive performance and reduce sensitivity of parameter variations, nonlinear effects, and other disturbances such as load changes and backlash. The matching model is used to identify the H^∞ tuning controller with bounded noise energy and minimized tracking error. An algorithm based on discrete Ricatti equation and H^∞ interpolation theory is used to solve the uncertain internal modeling and noise measurement issues in the tracking control system. The adaptive tuning controller effectively controls the presence of external disturbances, and identifies the rapid jumping and slow changing trajectory of the system. The effectiveness of the H^∞ model matching controller for the motor tracking control system is demonstrated by using the developed H^∞ adaptive tuning software controller. The H^∞ model matching control method is examined through computer simulation, and then tested in a real time microprocessor-controlled drive system. Experimental results based on PC based microcomputer implementation are presented to illustrate improved response and robust performance.

Keywords: H^∞ model matching, tracking control system, bounded noise, adaptive tuning.

I. INTRODUCTION

Following the output of a system track from a given reference trajectory is a common industrial problem. Sometimes the mechanical load varies considerably, but the trajectory of the motor drive still has to follow the required tracking operation. These situations can be found in typical examples, such as: robot joints, and machine tools[1][2][8][9][10]. All these motion systems require the motor bore the load changing and still keep the prescribed trajectory.

The motion disturbance in the above description accords to the uncertainty noise under modeling system which has to be minimized. It is the aim to make the motor drive system to meet the robust stability of control performance. And in order to obtain the satisfactory tracking performance[7], the adaptive tuning controller is usually considered in the linear on-line control strategy for a successful application[1]. However, it needs to design a reasonably accuracy model, or the resulting control algorithm is hard to maintain the tracking system in the robust stability. Envisioned the performance exploited by robust stable modeling operation in the sense, it is believed that the controller should be designed to have abilities to bound the noise disturbance and minimize the tracking error.

In this paper, a motor tracking control design using H^∞ model matching is proposed. It is designed to exclude the noise spectral densities whereas the conventional approaches can not. The merits of the approach lie in the simplicity of the scheme and its practicality for real-time implementation.

The identification has to be carried out within internal model matching condition. In order to make sure that a control transient can be concluded already with the desired response, the identification and the adaptation of the controllers have to be performed as fast as possible. The limited time needed for updating the controllers is determined by the convergence time of the identification algorithm and the time needed to calculate the new controller setting.

0-7803-2646-6

Generally, electrical drives are nonlinear systems because of current, voltage and speed boundaries. In addition, their parameters, e.g. resistance, inductance, moment of inertia, can vary. Also in real drive systems, the disturbances, e.g. load torque on the motor shaft, must be considered. The non-linearity of load torque and mechanical dampers is the main factors to make the tracking misalignment and system unstable[7]. In this paper, the system model of permanent-magnet DC motor is adopted to verify the tracking performance and robust stability.

Fig.1-1 is the block scheme diagram of main sections. Brushless dc motor represents in the dotted box. Inverted commutation circuit shows within the dashed line. The others of the diagram are included with the controller. Two input signals of the system from the current sensing which is proportional to the motor voltage and the increment encoder determine the rotor position.

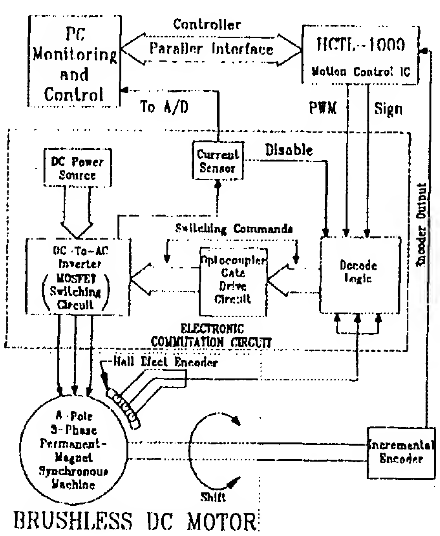

Fig.1-1 The hardware scheme diagram of motor main system

II. DYNAMIC MODEL OF PERMANENT MAGNET MOTOR DRIVE SYSTEM

The permanent magnet motor drive can be regarded as direct current by having d-q axes transformation that rotates synchronously with the alternating current. Because the relative velocity between the rotor shaft and stator becomes zero, making the dynamic model simpler. The relationship between voltage and current of a permanent magnet motor drive is as follows:

$$\begin{bmatrix} E_d \\ E_q \end{bmatrix} = \begin{bmatrix} R_a + p\,L_a & -\omega_m L_a \\ \omega_m L_a & R_a + p\,L_a \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \omega_m \phi \\ 0 \end{bmatrix} \quad (2\text{-}1)$$

Usually, iq make the minor effect in the controlled motor system. Therefore, the id current of the motor produce the strong control factor in the system. From eqn (2-1) Ed, Eq are the motor's terminal voltage in the steady state. The dynamic electrical circuit model is derived as:

$$d\,i_d/dt = -R_a/L_a\, i_d - \phi\,\omega_m/L_a + E_d/L_a \quad (2\text{-}2)$$

The instantaneous torque T_l is

$$T_l = J_l\,\dot{\omega}_m + B_m \omega_m + k\phi i_d \quad (2\text{-}3)$$

The system parameter is described as follows:

- R_a : the armature resistance
- L_a : the armature inductance
- J_l : the motor moment of inertia
- ϕ: the magnetic flux of the permanent magnet (constant).
- w_m : the angular velocity of the motor
- B_m : the coefficient of viscous friction
- $p = d/dt$
- T_l : the load torque
- E_d, E_q, i_d and i_q are d, q shaft voltages and currents.

From eqn (2-2) and (2-3) the transfer function of the permanent magnet motor drive with the variable disturbance load is shown in Fig.2-1.

The dynamic model of permanent magnet DC motor is well established in the continuous time domain by the state space model[13]:

$$\dot{x}(t) = \underline{A}x(t) + \underline{B}U(t) \quad (2\text{-}4)$$

where

$$x(t) = \begin{bmatrix} \theta_m(t) & \omega_m(t) & i_d(t) & i_q(t) \end{bmatrix}$$

$$U(t) = \begin{bmatrix} T_l(t) & E_d(t) & E_q(t) \end{bmatrix}$$

$$\underline{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -B_m/J_l & k_T/J_l & 0 \\ 0 & k_E/L_a & -R_a/L_a & 0 \\ 0 & 0 & 0 & -R_a/L_a \end{bmatrix}$$

$$\underline{B} = \begin{bmatrix} 0 & 0 & 0 \\ -1/J_l & 0 & 0 \\ 0 & 1/L_a & 0 \\ 0 & 0 & -1/L_a \end{bmatrix}$$

where

x(t) = state vector of the motor components.

U(t) = the disturbance (load torque) and the control signal (voltage)

A and B are system matrices corresponding to the input/output vectors, respectively.

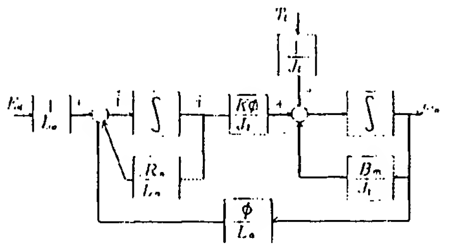

Fig. 2-1 Block diagram of a brushless DC motor

To protect the motor from overload in the motor tracking system. The motor system has specified constraints on the motor current. These limitations are as follows[2][7][11]:

(1) Peak current limitation: The maximum occurring motor is limited to avoid demagnetization of the permanent magnets.
(2) Continuous current limitation: To prevent the motor from overheating, the maximum constant current is limited to approximately half the peak current for the motor used. The continuous current limitation becomes active only after a certain period of time and can be disregarded in position control. However, if torque control is used, longer periods of maximum applied power can occur; in this case, the continuous current limited is important for the prevention of the power capacity of the driver components.
(3) Commutation limitation: The inrush current through the power drive components increases with the motor speed and the heavy load variation. To prevent the motor from being damaged, the product of armature current and voltage is limited.

In this paper, however, a systematic method is proposed to determine the plant orders and time delay of the motor tracking system[1][17]. To derive the computation equations, the time domain model of PM machine with a controller is transformed into the the discrete model in the z domain form, and generates the system upper bound for the worse case, as well as robust tracking output. The system is specified the requirement as followings:
speed bandwidth: 0 - 50Hz , under load condition and 12.5Hz for loading variation. The robustness is as large as possible within the setting frequency response. The accuracy of the position is within 1um, and no exciting phenomenon. Insensitivity of load disturbance and noisy interference is designed in the adaptive control scheme and modeling matching.

III. THE H$^\infty$ SYNTHESIS CONTROL CONCEPTS

First, the H$^\infty$ synthesis control system is structured as a standard problem, depicted in Figure 3-1. where the objective is to design a real-rational proper controller K such that the closed-loop system formed by real rational proper G and K is internally stable and the H$^\infty$ norm of the transfer function between external input vector v and controlled output vector z is minimized over all stabilizing controllers[3].

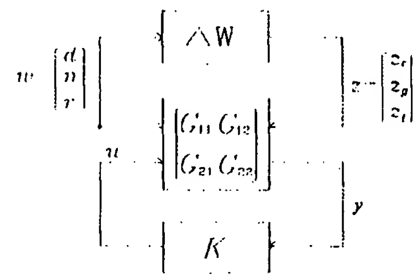

Fig. 3-1 H$^\infty$ synthesis standard problem

w : exogenous input vector included disturbance d, noise n, and reference order r.

z : controlled output vector included tracking error z_e, energy z_g, and output tracking z_t.

y : observed measured output vector.

u : controlled input state.

G : The augmented control model.

K : The feedback controller.

This augmented control system G can be written as:

$$G : G = C(qI - A)^{-1}B + D \quad (3\text{-}1)$$

The synthesis system can be represented as:

$$\begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}\begin{bmatrix} w \\ u \end{bmatrix} = \begin{bmatrix} z \\ y \end{bmatrix} \quad (3\text{-}2)$$

Setting the system gain K for feedback as:

$$u = Ky \quad (3\text{-}3)$$

The convergence and stability of the system can be obtained from inputs w to the outputs z of the close loop function. The form is expressed as:

$$z = T_{zw}(G, K)w \quad (3\text{-}4)$$

$$T_{zw} = G_{11} + G_{12}K(I - G_{22}K)^{-1}G_{21} \quad (3\text{-}5)$$

Eqn(3-5) represents the standard form of H^{∞} synthesis control system. The augmented synthesis system has to find the controller K so that

$$\inf_{K}\left\| G_{11} + G_{12}K(I - G_{22}K)^{-1}G_{21} \right\|_{\infty} \qquad (3\text{-}6)$$

The controller K [4] has to satisfy the following two conditions:

(i) The closed loop system is internally stable.

(ii) $\min\left\| T_{zw}(G,K) \right\|_{\infty} < \gamma \qquad 0 < \gamma < 1$

The augmented control system G means the combination of the real control system P and filter functions $\wedge$W for the tracking error and the internal system entropy. The filter function we adopt in this article shall consider the response of the output tracking as well as the minimized sensitivity for the system stability thereby boosting the system's performance and robustness.

The synthesis H^{∞} system is examined in reconstruction state space forms[5][6]. The mean square reconstruction error value is to measure the observer's reconstruction status. To design a time varying tuning procedure as follows:

$$Q(n+1) = \hat{A}(n)Q(n)\hat{A}^{T}(n) + W_1(n) \qquad \text{(pre-covariance)} \qquad (3\text{-}7)$$

$$L(n+1) = Q(n+1)\hat{C}^{T}(n+1)[\hat{C}(n+1)Q(n)\hat{C}^{T}(n+1) + W_2]^{-1} \qquad \text{(state estimation gain)} \qquad (3\text{-}8)$$

$$Q(n+1) = [I - L(n+1)\hat{C}(n+1)]Q(n) \qquad \text{(observed covariance)} \qquad (3\text{-}9)$$

From the above adaptive procedure, the synthesis H^{∞} system shall be examined from the predictor-corrector state.

$$\hat{x}(n+1) = \hat{A}(n)\hat{x}(n) + \hat{B}(n)u(n) + L(n+1)\{ y(n+1) - \hat{C}(n)[\hat{A}(n)\hat{x}(n) + \hat{B}(n)u(n)]\} \qquad (3\text{-}10)$$

IV. THE ADAPTIVE MODELING IDENTIFICATION

The dynamic model of PM DC motor is well set up by the augmented system that is translated into the difference equation necessary for use in the discrete system[15].

The discrete form is given by eqn (4-1) in the state space model:

$$\bar{y}_t = \bar{A}(n-1)\bar{x}(n-1) + \bar{B}(n-1)\bar{u}(n-1) \qquad (4\text{-}1)$$

The matrices $\bar{A}(n-1)$, and $\bar{B}(n-1)$ in discrete-time model are based on the motor's parameters in eqn (2-4).

The approach to make the identification of a motor trajectory employs the QR based method to solve the recursive least square(RLS) problem. The QR based method is numerically stable. It shows that the computation method of matrix problems is for orthogonal similarity transformation.

To do so in the adaptive tuning procedure[17], the objective is to finally obtain a predictor model for the desired tracking y_t:

$$y_t(n) = X^{T}(n)\,\theta(n) + \zeta_t \qquad (4\text{-}1)$$

where $X^{T}(t)$ is an observed vector using past values of y_t and X. $\theta(t)$ is a parameter vector using the coefficients from the above of $A(n\text{-}1)$ and $B(n\text{-}1)$, and ζ_t is an error variable representing the load disturbance and modeling error. From the QR based least squares computation, it is to see that generation of pseudo-linear variable y'_t, defined as

$$y'_t = T^{-1}AT\,X(n) \qquad (4\text{-}2)$$

The setting up recursive least square (RLS) model, keep the identification order low. A state space predictor for the plant model[14] can now be set up by a series of estimation steps.

error: $\quad e_t = y'_t - X(n)\hat{\theta}(n) \qquad (4\text{-}3)$

controller gain:

$$K_t(n) = -[\hat{B}^{T}P_{t-1}(n)\hat{B} + \lambda_{t-1}(n)]^{-1}\hat{B}^{T}P_{t-1}(n)\hat{A} \qquad (4\text{-}4)$$

estimate: $\quad \hat{\theta}_t(n) = \hat{\theta}_{t-1}(n) + K_{t-1}(n)e_t \qquad (4\text{-}5)$

forgetting factor:

$$\lambda_t(n) = I - (I + \hat{B}^{T}P_{t-1}(n)\hat{B})e_t^2/\Gamma \qquad (4\text{-}6)$$

covariance:

$$P_t(n) = [\hat{A} + \hat{B}K_t(n)]^{T}P_{t-1}(n)[\hat{A} + \hat{B}K_t(n)] + K_t^{T}(n)\lambda_t(n)K_t(n) \qquad (4\text{-}7)$$

$P_t(n)$ has to be positive semidefinite, and if $P_t(n)$ has rank defect r, then it needs to use an orthogonal transformation T to adjust it.

V. The Model Matching for the Motor System

The estimator of the system is reconstructed after every periodic computation. It consists of a set of time varying equations from eEqn (3-7) to eqn (3-10). These works can form an estimated system model. The controller of the augmented system is designed in accordance with eqn (4-2) to eqn (4-7). It executes in the state of the adaptive tuning to minimize the motor tracking error.

The H^{∞} approach design is needed to specify the disturbance from the input for the worse case. Therefore, the term gamma γ is required to setup for the robust range.

$$\sigma\left(P_t(n)Q(n)\right) < \gamma^2 \qquad (5\text{-}1)$$

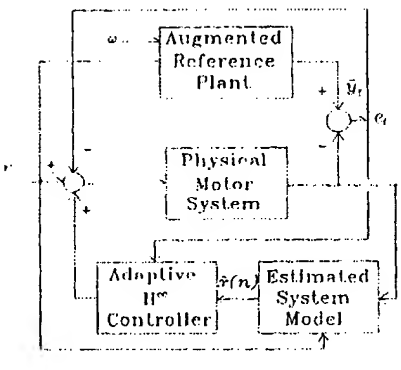

Fig. 5-1: The H$^{\infty}$ synthesis model control system

It means that the spectral radius of $P_l(n)Q(n)$ must be lower than the upper bound of disturbance γ.

Fig.5-1 shows the H$^{\infty}$ synthesis control scheme model for the motor control system. From the figure 5-1 the estimated system model is derived from the real motor system and the desired augmented reference plant. The adaptive H$^{\infty}$ controller is designed after the system model [16] is estimated.

VI. TEST RESULTS

Several test cases in the experiment evaluate the proposed H$^{\infty}$ approach model matching technique.

The position track selected in this test is composed of three segments of sigmoidal functions. The first rotates the forward position by 200 radian, the second is holding the position at 200 radian for 2 second, and the third turns the reverse direction back to the original position by the armature current braking from the feedback sensor signal. In these test cases, the armature surge current is limited within the specified range to verify the motor system running within the designed tracking and safety working condition.

Two cases are shown on the following mainly to represent the trajectories of the motor rotor position and required speed tracking paths. Each of the motor system tracking is measured from the starting time and sampled in every 20 msec.

Case I shows figures from Fig.6-1 to Fig.6-10 to examine the motor system performance and robust. Case I represents 10% perturbation with the required trajectory entering the motor system and the load torque changing periodically every 12.5Hz. Figure 6-1 to 6-7 shows the tracks and the measurements of the rotor position, speed, voltage, and electric torque, position tolerance, direct current, and quardrature current, respectively. The dotted line on Fig. 6-1 and Fig. 6-2 represents the desired trajectory, while the the dash line represents the output trajectory. The position trajectory follows the desired sigmoidal tracking on Fig. 6-1. The speed trajectory gets some disturbance but still maintain the set speed

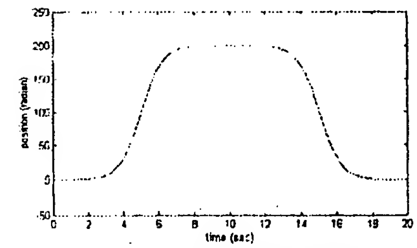

Fig. 6-1 Case I: Position trajectory

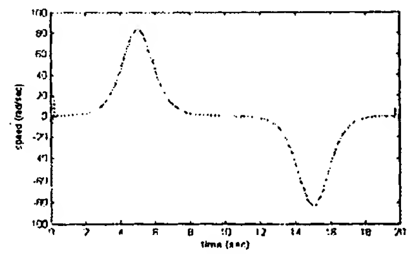

Fig. 6-2 Case I: Speed trajectory

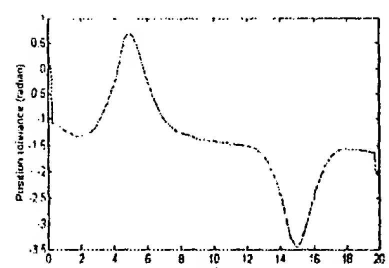

Fig. 6-3 Case I: Position tolerance

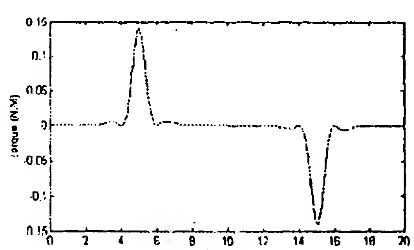

Fig. 6-4 Case I: Electric torque

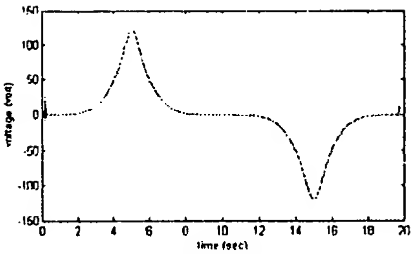

Figure 6-5 Case I: Armature voltage

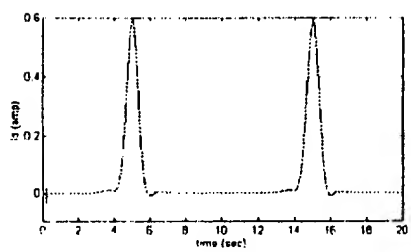

Fig. 6-6 Case I: Direct current

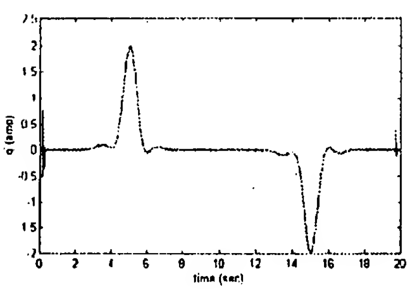

Fig. 6-7 Case I: Quardrature current

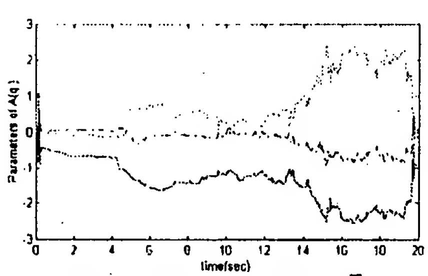

Fig. 6-8 Case I: Parameters of $\bar{A}(q)$

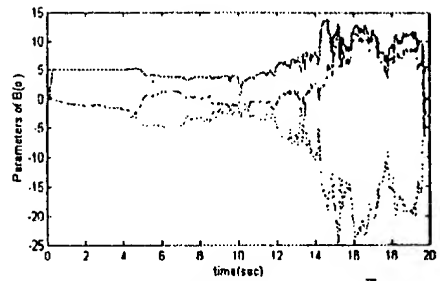

Fig. 6-9 Case I: Parameters of $\bar{B}(q)$

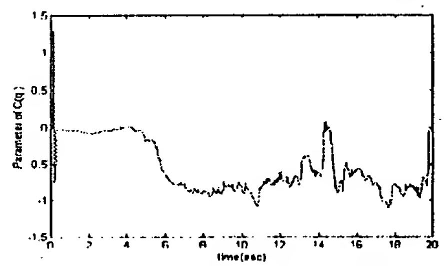

Fig. 6-10 Case I: Parameter of $\bar{C}(q)$

running on Fig.6-2. Fig. 6-4 shows the electric torque increased during the motor accelerating the speed. However, the motor system still maintains in the safe running condition by examining the voltage and current variation from Fig. 6-5 to Fig. 6-7.

The time varying motor system under the noise perturbation and load change highly depends on the adaptive tuning for the satble and robust synthesis system performance. Fig. 6-8 to Fig. 6-10 show the synthesis parameters of the H^∞ system. The parameters of matrices of $\bar{A}(q)$, $\bar{B}(q)$ and $\bar{C}(q)$ show the adaptive identification for the reduction order H^∞ approach matching. Specifically, when the motor proceeds the tracking in the braking segment, the system parameters vary quite largely.

To satify the robust performance of the H^∞ synthesis approach, it is designed the upper bound for the worse case at the gamma value (γ) 0.67 in Case I.

Case II represents the situation of the 50% uniform distributed perturbation with the desired trajectory entering the motor system and the load torque changing periodically every 25Hz. Fig. 6-11 to Fig. 6-15 shows the performance of the motor system in case II. It examines the motor system with the robust control In the H^∞ synthesis approach. In Case II, the gamma term γ is designed 0.45 for the robust range. It can meet the case to limit the upper bound of disturbance.

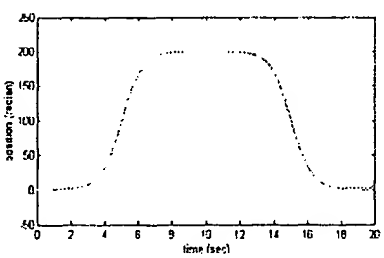

Figure 6-11 Case II· Position trajectory

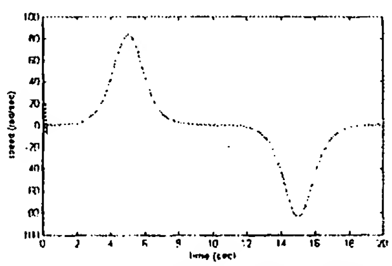

Fig. 6-12 Case II: Speed trajectory

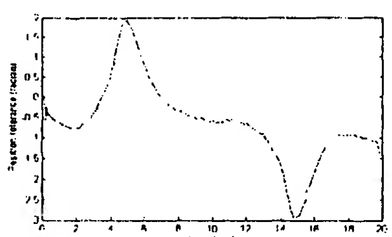

Figure 6-13 Case II: Position tolerance

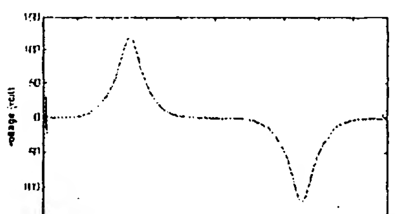

Fig. 6-14 Case II: Armature voltage

The dotted line on Fig. 6-11 and Fig. 6-12 represents the desired trajectory, while the the dash line represents the output trajectory. Fig. 6-11 shows the position trajectory following the desired tracking under the heavy

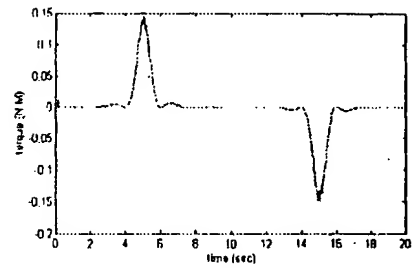

Fig. 6-15 Case II: Electric torque

noise and load varying. It can be seen from Fig. 6-13 that the position trajectory has one step predicted error, especially, during the motor increasing speed. However, the dc error of the position trajectory is derived from the uncertainty disturbance. It can be compensated to adjust the deadbeat of the filter.

In this paper, it mainly emphasizes the performance of the position trajectory. Therefore, the speed trajectoryon Fig. 6-12 is infected by some disturbance similarly as Case I, during the motor starting, speedup, and braking stop. Fig. 14 and Fig. 15 show the motor system still stable when the strong perturbation adds to the system. In Case II it still can work within the protected safty range.

Fig. 6-13 shows that the larger position tolerance appears as the disturbance become larger, comparing with Case I. It shows that the dc tolerance is reduced by adding the constant backlash. However, it is designed from the synthesis system to bound the disturbance in the spectral radius.

VII. CONCLUSIONS

In this paper, the design and implementation of an H^{∞} matching controller with an adaptive tuning has been investigated. A synthesis systematic and analysis approach for developing the algorithm is presented. The H^{∞} filter is tuned by various parameters $Q(n), L(n), K(n), \lambda(n), P_i(n), and\ X(n)$ which are dominant in the state identified model and the designed H^{∞} controller. These parameters have to meet the desired transient and steady state performance. The discrete adaptive H^{∞} matching controller has been designed to be well suited the motor speed and position trajectory for Brushless DC motor. The load torque variation and mechanical damper can be immunize by the designed H^{∞} controller under the upper bound area. The next step in this research will test the H^{∞} matching

controller in different kinds of disturbance for the speed and position trajectory.

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